Localization of brain activity associated with non-time-locked tactile stimulation using synthetic aperture magnetometry (SAM)

D. Cheyne[1], G.R. Barnes[2], I.E. Holliday[2], and P. L. Furlong[2]

[1]*School of Kinesiology, Simon Fraser University, Burnaby, B.C. and CTF Systems Inc, Port Coquitlam, B.C. Canada;* [2]*Wellcome Trust Laboratory for MEG Studies, Neurosciences Research Institute, Aston University, Birmingham, U.K.*

1 Introduction

It is well know that changes in spontaneous brain rhythms accompany both sensory stimulation and motor activity in humans and that such changes arise from sensorimotor areas of the cortex[1-3]. In particular, sensory input has been observed to suppress activity in both centrally distributed alpha or mu (8-15 Hz) and beta (15-25 Hz) frequency bands and there is evidence that there is a rebound of this activity following electrical stimulation of the digits [1]. Furthermore, such rebound phenomena appear to arise from the hand area of the postcentral gyrus and can be influenced by ongoing motor activity or even motor imagery [1,4].

In the current study, we apply a new method, synthetic aperture magnetometry (SAM) [5,6] to localize frequency specific changes in sensorimotor cortex during passive tactile stimulation. SAM is a minimum variance beamformer which allows three-dimensional localization of source activity at an arbitrary spatial resolution without the need for signal averaging, or *a priori* specification of the number of active sources.

In the current study we compute SAM difference images of source power integrated over 4 s time windows between finger brushing (active) versus rest (control) periods, and superimposed these images on structural MRI scans for each subject.

2 Methods

2.1 Data Acquisition

Neuromagnetic responses were recorded from two subjects using a 151-channel whole-cortex MEG system (CTF Systems, Inc) in a magnetically shielded room. Signals were collected at a sample rate of 2083 samples/s with a bandwidth of DC to 400 Hz. Twenty epochs of 10 seconds duration were collected during which the palmer surface of the subject s right index finger was gently stroked with a bristle brush for 5 seconds (active state) followed by 5 seconds of rest (control state) as shown in Fig. 1. This procedure was repeated twice for each subject and in addition electrically evoked SEFs for the same digit was recorded separately in one subject (sample rate 2083 samples/s, bandpass DC-400, n=200) using ring electrodes around the middle and distal phalanges of the right index finger (0.2 ms duration pulses, 2.3 pulses / sec, 2.5 times sensory threshold). Accurate co-registration of the MEG sensors and the MRI images was achieved by fitting the subject s digitized head shape to the extracted MRI scalp surface.

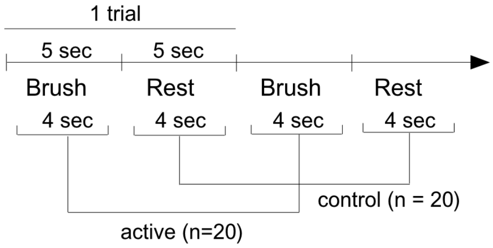

Figure 1. Experimental paradigm. Periods of tactile stimulation of 5 s duration were alternated with periods of rest. Active and control states were extracted segments of each stimulation period (active = 0.5 — 4.5 s; control = 5.5 — 9.5 s).

2.2 Synthetic Aperture Magnetometry (SAM)

Three-dimensional imaging of brain activity was performed using a new type of spatial filtering algorithm referred to as synthetic aperture magnetometry or SAM [5]. SAM is a type of minimum variance beamformer. Beamformers construct a spatial filter for a selected point in space (target voxel) such that the filter output is a linear combination of the measurements over time **m**(t) as

$$\hat{S}_{\theta}(t) = \mathbf{W}_{\theta}^{\mathrm{T}}\mathbf{m}(t) \qquad (1)$$

where $\mathbf{W}_{\theta}$ represents the weight vector for the target voxel. While conventional beamformers [7] determine power corresponding to a selected location without regard to source orientation, the SAM beamformer is four-dimensional [5], in the sense of being sensitive to both voxel location and source orientation. (i.e., θ denotes both target voxel position and orientation). As a consequence of this four-dimensional parameterization, it can be shown that SAM filters exhibit better spatial resolution than conventional beamformers [6]. The weights $\mathbf{W}_\theta$ are determined by minimizing the source strength power (Eq. 1) subject to the requirement that the beamformer gain corresponding to the location parameter θ is unity:

$$\mathbf{W}_\theta^{\mathrm{T}}\mathbf{B}_\theta \equiv 1. \qquad (2)$$

where $\mathbf{B}_\theta$ denotes the target voxel forward solution (per unit dipole moment) for the selected current direction. The procedure yields [5]

$$\mathbf{W}_\theta = \left[\mathbf{C} + \mu\Sigma\right]^{-1}\mathbf{B}_\theta\left[\mathbf{B}_\theta^{\mathrm{T}}\left(\mathbf{C} + \mu\Sigma\right)^{-1}\mathbf{B}_\theta\right]^{-1} \qquad (3)$$

where, Σ denotes a diagonal matrix of estimated sensor noise power, **C** the covariance matrix, and μ a regularization parameter which adjusts the trade-off between spatial resolution of the filter and its sensitivity to noise. In the current study this regularization parameter is set to a value of zero for maximum spatial resolution of the beamformer. Note that the constraint imposed in Eq. 2 provides normalization of the output to units of source strength. Since signal-to-noise decreases with increasing source depth in biomagnetic measurements, the influence of uncorrelated noise projected by the beamformer also increases. As a result it is useful to use the ratio of the estimated source power to the estimated projected (uncorrelated) noise power for constructing images of source power over large regions of the brain [7]. In the current analysis we calculate differences in source power at the target voxel for active and control states using a pseudo-T statistic [5] given by,

$$T_\theta = \frac{{}^{(a)}\hat{S}_\theta - {}^{(c)}\hat{S}_\theta}{{}^{(a)}\hat{v}_\theta + {}^{(c)}\hat{v}_\theta} \qquad (4)$$

Eq. 4 provides an estimate of differences in source power ($\boldsymbol{S}_\theta$) between the active (a) and control (c) states, normalized by the sum of the estimated projected power due to sensor noise ($\boldsymbol{v}_\theta$).

2.3 Data Analysis

Volumetric difference images were constructed by computing the SAM filter for voxels at a 2 mm spacing over a 3-dimensional volume encompassing the upper half of the brain and integrating differences in source power over time windows of 4 s duration constituting the control and active periods. As shown in Fig. 1 time windows were selected from the middle of each active and control period from each of the twenty 10 second trials (80 seconds of data total per condition) in order to exclude stimulus onset and offset. SAM images were reconstructed for specific frequency bands of interest (alpha and beta) by band limiting the data and covariance matrix used to form the weights, and then converted to pseudo-T values as described in Eq. 4. The resulting volumetric images were then automatically scanned for peak areas of activation and the 3-dimensional coordinates stored for each location.

To examine in more detail the frequency specificity of changes at locations of peak activation, larger bandwidth (1-50 Hz) SAM filters were constructed from the combined active and control states for voxels which showed the largest change in source power. These weights when applied to the bandpass filtered single trial data provide waveforms of time dependent output of the beamformer for each location. FFT spectra were then computed for time windows corresponding to the active and control states separately and averaged to compare the frequency changes in peak voxel activity for the two states.

3 Results

3.1 Volumetric SAM Analysis

The volumetric SAM images showed a clear decrease in power near the hand area of the contralateral sensorimotor cortex in both alpha (8-13 Hz) and beta (15-25 Hz) frequency bands in both subjects as shown in Fig. 2. These focal decreases near SI were the dominant frequency changes observed in the cortex and were consistent across subjects and repeated recordings within subjects. Although decreases in power were observed in both alpha and beta frequency bands, images computed for the alpha band tended to show the most focal activation in contralateral SI in close proximity (< 1 cm) to the equivalent current dipoles source fitted to the early (25 ms) component of the averged somatosensory evoked response as shown in Fig. 3.

Interestingly, smaller decreases in source power were also observed in the ipsilateral somatosensory cortex, and bilaterally near the parietal operculum (SII) although the latter tended to be more variable in location and distributed across frequencies including frequencies below the alpha band.

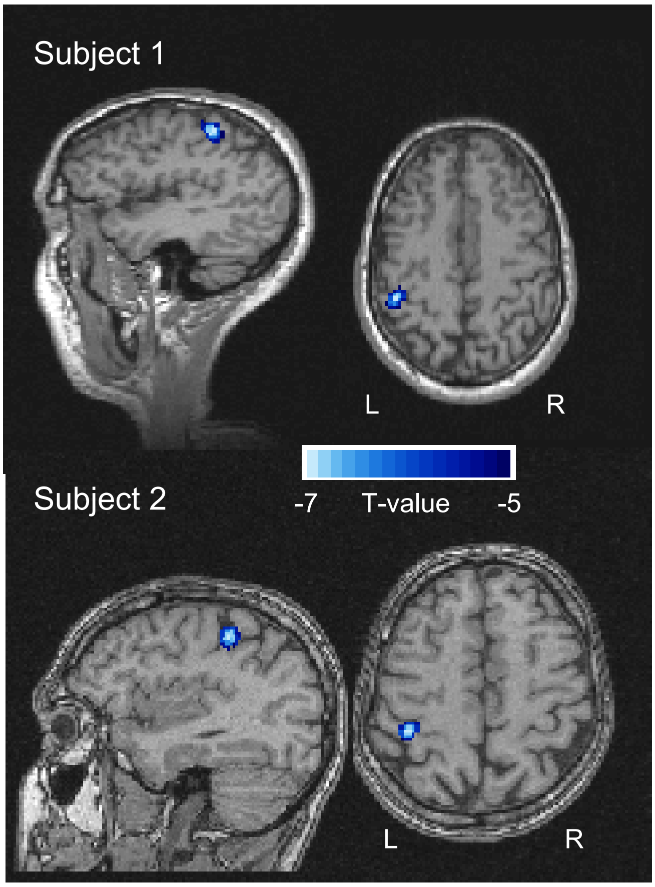

Figure 2 SAM (pseudo-T) difference images superimposed on sagittal and axial MRI slices showing a decrease in 8-13 Hz band in SI during tactile stimulation. Colour intensity indicates the level of decrease in source power. Images were constructed at 2 mm resolution and thresholded to values below —5.0.

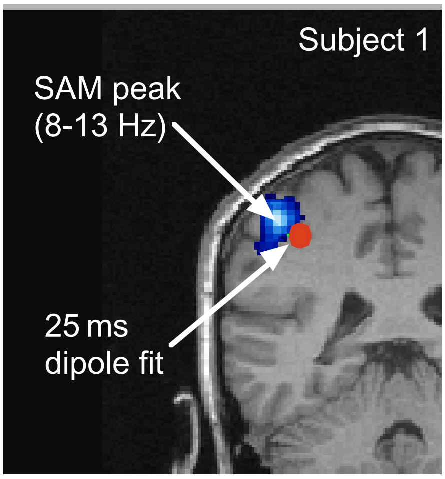

Figure 3. Comparison of peak alpha band decrease in SAM image and location of equivalent dipole fit to the 25 ms component of finger SEF.

3.2 Peak Voxel Frequency Analysis

In the volumetric images described above, multiple areas of decreased source power were detected in different frequency bands. Fig. 4 shows three main areas detected for the alpha band in one subject showing peaks in both contralateral primary somatosensory cortex (SI-c), ipsilateral primary somatosensory cortex (SI-i) and in the vicinity of the contralateral secondary somatosensory cortex (SII-c). Note also a small decrease in the ipsilateral SII. Since different areas of decreased power (desynchronization) appear in different frequency bands, we produced SAM filters for the peak voxels of each area and produced averaged frequency spectra of the filter output as described in the Methods section. Fig. 5 shows the power spectra corresponding to the target areas identified in Fig 4.

4 Discussion

This preliminary application of SAM imaging analysis to study frequency changes in brain areas during continuous sensory stimulation was able to show marked reduction of spontaneous brain rhythms (desynchronization) in both alpha and beta bands during tactile input to the fingers. Comparison to dipole fits to the electrically evoked response from the same finger indicates that these changes are maximal in primary somatosensory cortex (SI) but also involve ipsilateral SI. These findings are consistent with other studies showing that central alpha activity (also referred to as mu rhythm) appears to originate from the postcentral gyrus [1,4] and is suppressed by somatosensory input.

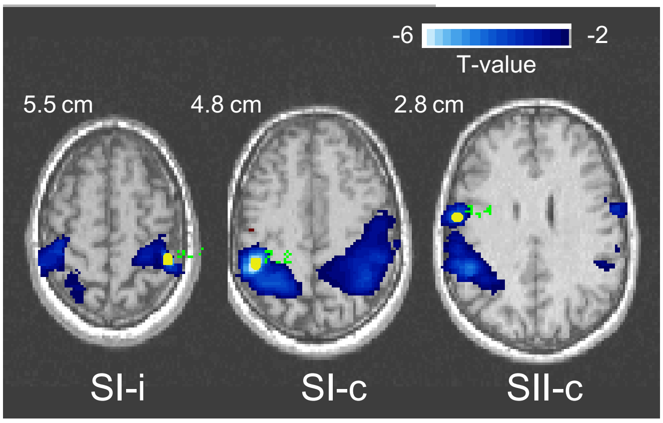

Figure 4. SAM (pseudo-T) difference image showing main areas decrease in source power in the alpha band (8-13 Hz) in one subject. T-value threshold decreased to show additional background activity. Peak values indicated by yellow dots.

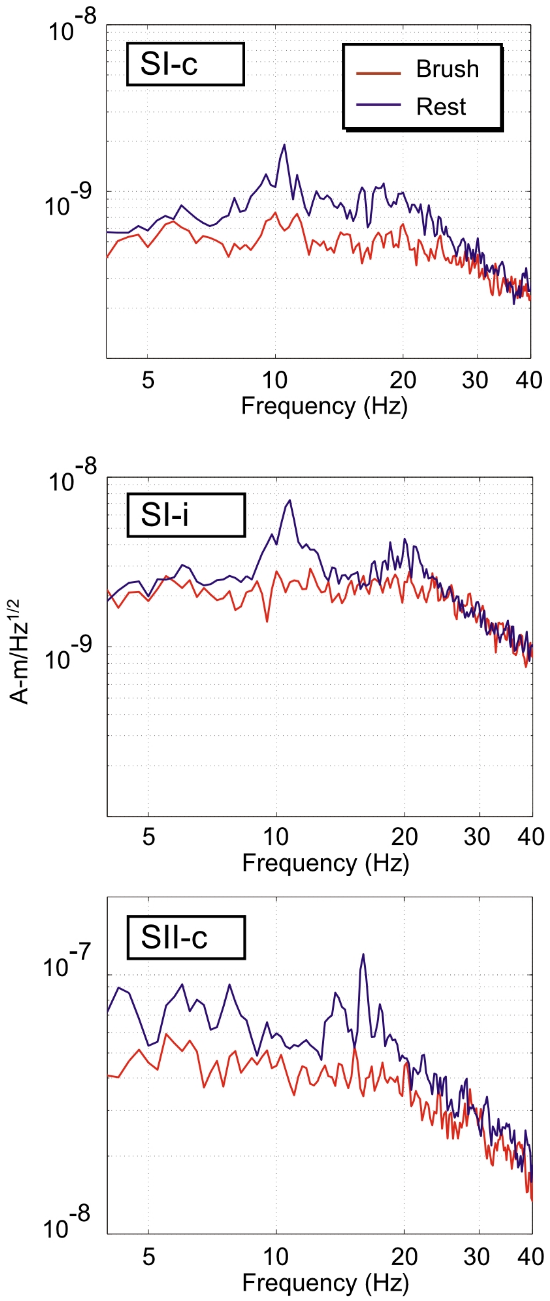

Figure 5. Averaged FFT spectra of SAM filter output for peak voxels shown in Fig. 4.

Interestingly, lowering of the threshold for filter output as shown in Fig 4. indicates that changes in alpha activity are prevalent over the entire sensorimotor strip indicating that this brain area is dominated by background alpha activity which is selectively suppressed in the hand area during stimulation. However, changes are also detected in the beta band during this task which is known to play an important role in sensorimotor integration [8]. In conclusion, our results indicate that SAM image analysis is able to demonstrate frequency specific changes in sensorimotor cortex without the need for signal averaging or *a priori* dipole models and may provide a useful tool for the study of changes in spontaneous brain activity in paradigms that are not amenable to signal averaging of time locked sensory stimulation.

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